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A Binary Study of Colour-Magnitude Diagrams of 12 Globular Clusters

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Abstract Binary stars are common in star clusters and galaxies, but the detailed effects of binary evolution are not taken into account in some colour-magnitude diagram (CMD) studies. This paper studies the CMDs of twelve globular clusters via binary-star stellar populations. The observational CMDs of star clusters are compared to those of binary-star populations, and then the stellar metallicities, ages, distances and reddening values of these star clusters are obtained. The paper also tests the different effects of binary and single stars on CMD studies. It is shown that binaries can fit the observational CMDs of the sample globular clusters better compared to single stars. This suggests that the effects of binary evolution should be considered when modeling the CMDs and stellar populations of star clusters and galaxies.

Key words: (Galaxy:) globular clusters: general — galaxies: star clusters

1 INTRODUCTION

Star cluster is a kind of important object in astrophysical studies. The colour-magnitude diagrams (CMDs) are usually used to determine the properties of star clusters, i.e., stellar age, metallcity, distance, and reddening values (see, e.g., Naylor & Jeffries 2006, and Kalirai & Tosi 2004). In most works, the theoretical isochrones of some single-star simple stellar populations (ssSSPs) (e.g., Momany et al. 2003) are used , because their corresponding CMDs are shown as simple curves and are convenient for studies. Meanwhile, some works use observed template CMDs (Recio-Blanco et al. 2005) for similar studies. Recently, some works have tried to study the CMDs of star clusters via more advanced techniques, i.e., Monte Carlo simulations. One can refer to the papers, e.g., Kalirai & Tosi (2004), Aparicio et al. (1990), Tosi et al. (1991), Hurley & Tout (1998), Skillman & Gallart (2002), for more information. Such methods are more advanced and can give additional parameters such as binary fraction and star formation histories to star clusters. This is an important progress because these methods take the effects of binaries into account. Although the new methods are much more informative and rewarding, they usually need more constraints on the properties of star clusters from independent techniques to make the fitting exercisable, and such methods are used to study some star clusters with accurate observed CMDs. Therefore, it is difficult to study the CMDs of a big sample of star clusters as the limitation of the accuracy of observed CMDs and known properties of star clusters. In addition, most works focus on the widening of the main sequences of theoretical CMDs when considering the binary effects in the comparisons of observational and theoretical CMDs (e.g., Naylor & Jeffries 2006). However, according to the works of Kalirai & Tosi (2004) and Li & Han (2008), binary evolution affects not only the shapes of some

special parts of CMDs, but also the number distributions of stars in CMDs. Therefore, it is necessary to take the detailed effects of the evolution of binaries in CMD studies.

According to the studies of Li & Han (2008) and Li & Han (2009), binary evolution can affect the integrated features of populations. Besides the widening of isochrones, binary evolution can explain some special stars such as blue stragglers in star clusters. They can also interpret the UV excess in elliptical galaxies (see, e.g., Han et al. 2007). Therefore, it is calling for CMD studies on the basis of some stellar populations that have taken the detailed effects of binary evolution into account. If the effects of binary evolution are taken into account, some different properties of star clusters may be obtained. This is helpful for understanding star clusters further. Furthermore, because stellar isochrone is a basic ingredient to build stellar populations, to compare the CMDs of star clusters with the synthetic CMDs of binaries can help us to model stellar populations in more advanced ways. This paper aims to study the CMDs of a few star clusters via binary stars, and then compare the results determined by binary- and single-star simple stellar populations (bsSSPs and ssSSPs). Because globular clusters (GCs) are usually thought to be simple systems that include metal-poor and old stars, we take some GCs as the star cluster sample of this study.

The paper is organized as follows. In Section 2, we introduce our sample GCs and their observational CMDs. In Section 3, we summarize the features of the theoretical CMDs of stellar populations. In Section 4, we present the binary fittings of the CMDs of star clusters and show the properties of GCs. In Section 5, we compare the results determined respectively by binary- and single-star populations. Finally, in Sections 6 and 7, we give our discussion and conclusions.

2 SAMPLE GLOBULAR CLUSTERS AND THEIR PHOTOMETRY

There are a lot of observational results for the CMDs of globular clusters and some ones are presented recently (e.g., Piotto et al. 2002, Kerber & Santiago 2005). We take some observational results from a catalogue of the UBV HR diagrams of globular clusters (Philip et al. 2006, hereafter Philip catalogue) for this work. The reason is that these observational data show some clear CMDs and seem reliable. In addition, photometry results have less uncertainties than spectral results, and the photometry source affects the final results slightly. Furthermore, we aims to try a binary way to study the CMDs rather than to obtain very accurate properties of star clusters. Thus the selected CMDs are suitable for this work. The Philip catalogue is of 65 color-magnitude diagrams of star clusters, which are compiled from the literature. Some star clusters in the catalogue are shown a few CMDs derived from different sources. When choosing the CMDs used in the work, some ones with better CMD shapes are taken. As a result, we choose twelve globular clusters from the catalogue. The twelve globular clusters are NGC104, NGC2419, NGC4147, NGC4372, NGC5272, NGC5897, M5, NGC6205, M10, NGC6352, NGC6397, and NGC6809. Note that all sample clusters contain more than 100 observed stars. This possibly makes the results more reliable.

3 THEORETICAL COLOUR-MAGNITUDE DIAGRAMS

Theoretical CMDs are basic ingredients of the work. This work uses two kinds of theoretical CMDs, i.e., the CMDs of bsSSPs and ssSSPs. Both the two kinds of theoretical CMDs are built on the basis of an isochrone database of stellar population studies (Li & Han 2008). For convenience, we take a Salpeter shape (Salpeter 1955) for the initial mass function of theoretical stellar populations. When modeling binary-star stellar populations, a fraction of 50% is taken for the binaries that have orbital periods less than 100 yr (typical value of Milky Way Galaxy), and the lower and upper mass limits are set to be 0.1 and 100 mass of solar, respectively. The stellar evolution is calculated by a rapid star evolution code of Hurley et al. (2002) (hereafter Hurley code). In each bsSSP, binary interactions such as mass transfer, mass accretion, common-envelope evolution, collisions, supernova kicks, angular momentum loss mechanism, and tidal interactions are considered. Some default parameters of the Hurley code, i.e., 0.5, 1.5, 1.0, 0.0, 0.001, 3.0, 190.0, 0.5, and 0.5, are taken for wind velocity factor ($\beta_{\rm w}$), Bondi-Hoyle wind accretion faction ($\alpha_{\rm w}$), wind accretion efficiency factor ($\mu_{\rm w}$), binary enhanced mass loss

parameter ($B_{\rm w}$), fraction of accreted material retained in supernova eruption (ϵ), common-envelope efficiency ($\alpha_{\rm CE}$), dispersion in the Maxwellian distribution for the supernovae kick speed ($\sigma_{\rm k}$), Reimers coefficient for mass loss (η), and binding energy factor (λ), respectively. These values are taken because they have been tested by Hurley et al. (2002) and seem more reliable than other ones. One can refer to the paper of Hurley et al. (2002) for more details. Therefore, many of these free parameters remain large uncertain, and they are needed to be studied detailedly in the future. Accordingly, this work is limited by the isochrone database, although it is a convenient choice. In addition, the BaSeL 2.2 photometry library (Lejeune 1998) is used when transforming the isochrone database into the CMDs of bsSSPs and ssSSPs.

4 BINARY FITTING OF COLOUR-MAGNITUDE DIAGRAMS OF GLOBULAR CLUSTERS

Basing on the theoretical CMDs of bsSSPs, we fit the CMDs of our sample clusters and derive some basic parameters of these clusters in this section. In order to get reliable results, big ranges are taken for the stellar ages and metallicities of theoretical populations when fitting the observational CMDs of star clusters. In detail, the stellar age and metallicity ranges are taken as 0.1 – 15 Gyr and 0.0001 – 0.03, respectively. These are just the default ranges of the isochrone database used by this work. Although the largest metallicity of the theoretical populations is only 0.03, it is enough for studying the CMDs of most globular clusters, as globular clusters are usually metal-poor ($Z \leq 0.03$). Because the observational data of stars with high luminosities have less observational uncertainties, a magnitude-weighted method is taken in this work. This can possibly enhance the reliability of the fitting results. For clearly, we show the comparison of the observational and best-fit theoretical CMDs of 12 GCs in Figs. 1, 2 and 3. The best-fit CMDs are found by comparing the distribution of stars in theoretical CMDs to that in observational CMDs. The advantage of such a method is that both the shape and luminosity function are compared at the same time.

From the three figures shown we can see that the main shapes of the CMDs of star clusters are well reproduced. Therefore, the the properties of star clusters derived from the CMD fitting are reliable. In detail, the stellar ages, metallcities, distances, and reddenings determined by comparing observational CMDs to synthetic CMDs are listed in Table 1. It shows that these clusters have a minimum age of 4 Gyr and a maximum age of 13 Gyr, with an average of 11.42 Gyr. The lowest and highest metallicities (Z) of these globular clusters are 0.0001 and 0.01, respectively, which has an average of 0.00145. As a whole, the results show old ages and poor metallicities for globular clusters. This is in agreement with most previous studies.

5 COMPARISON OF DIFFERENT RESULTS

Some bsSSP models are used for studying the CMDs of globular clusters in this work, but most other works use ssSSP models. In order to investigate the differences between the CMD studying results derived from bsSSP and ssSSP models, we compare the observational CMDs of two globular clusters (M5 and NGC6397) with those of theoretical bsSSPs and ssSSPs. The two clusters are chosen for the study because their CMDs are intact. In Fig. 4, the detailed comparison of the observational CMDs with the best-fit theoretical CMDs of bsSSPs and ssSSPs is shown. We see that the CMDs of best-fit bsSSPs cover larger ranges in the colour versus magnitude field compared to the best-fit ssSSPs, and the CMDs of bsSSPs are actually closer to the observational CMDs of the two globular clusters. When comparing the properties determined by bsSSPs and ssSSPs, they are shown to be different. In detail, the best bsSSP fit age, metallicity, distance modulus in V band, and reddening $E(B-V)$ of M5 are 9.5 Gyr, 0.0003, 14.8 mag, and 0.12 mag, while the ssSSP fit results are 12.6 Gyr, 0.0001, 14.75 mag, and 0.15 mag, respectively. The other star cluster, NGC6397, is shown some bsSSP fit properties of 11.4 Gyr (age), 0.0001 (metallicity Z), 13.2 mag (distance modulus), 0.1 mag (reddening), with ssSSP results of 13.6 Gyr, 0.0001, 13.0 mag, 0.15 mag, respectively. Because the same method was used for the bsSSP and ssSSP fitting, the differences result from the stellar population models.

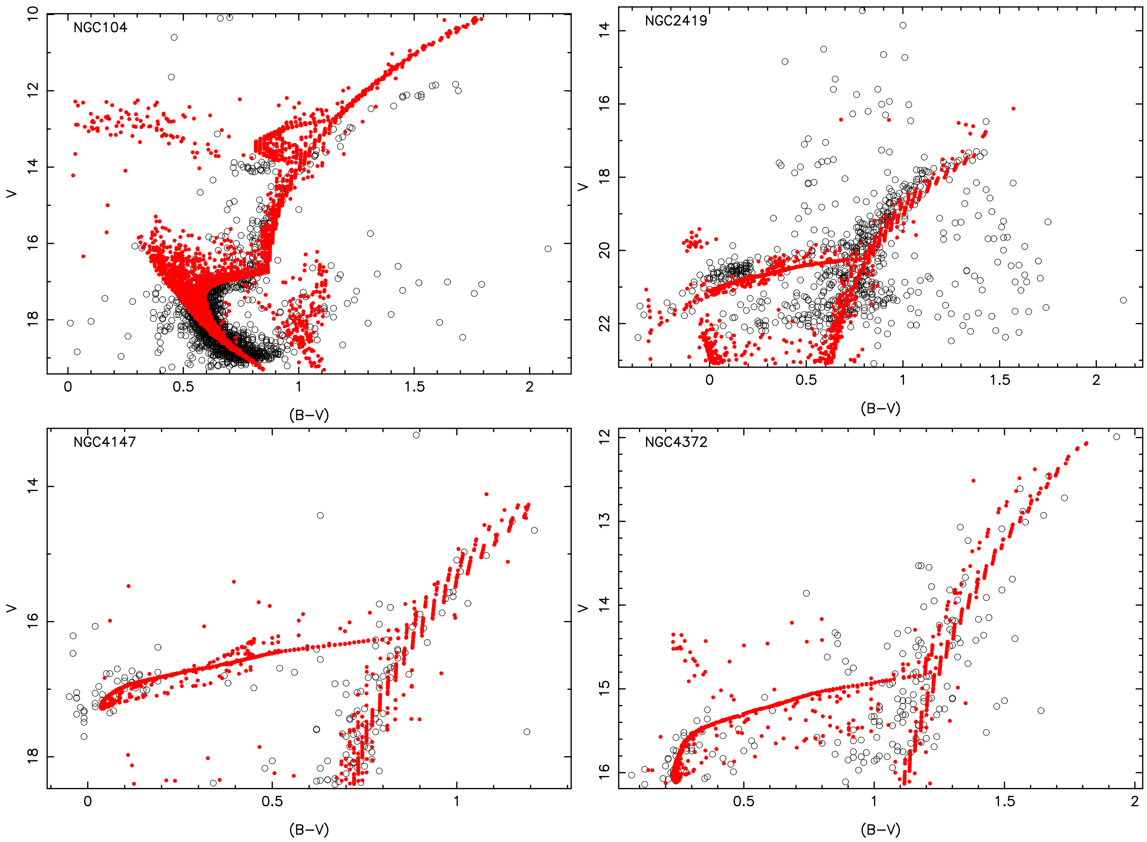

Fig. 1 Comparison of observational (black circles) and best fit theoretical (red points) CMDs, for globular clusters NGC104, NGC2419, NGC4147, and MGC4372, respectively. The theoretical CMDs are calculated from binary-star populations with 50% binaries and each star is assumed to be discriminable. In the field shown in the figure, the observational and theoretical CMDs contain the same stars, but a few red points contain less than 1 star.

6 DISCUSSION

Binary stars can explain the observational CMDs of globular clusters as a whole, but it is clear that there are some differences between the observational and theoretical CMDs. This possibly results from the following reasons: First, there are some limitations in our theoretical stellar populations. For example, the basic inputs (e.g., binary fraction, initial mass function) of the bsSSP model remain some uncertainties and the metallicity intervals are not enough small. Note that the binary fractions in GCs are possibly lower than those ($\sim$ 50%) in in the local fields, open clusters, and star-forming regions, because frequent dynamical interactions together with binary evolution processes conspire to destroy binaries in GCs effectively. Second, it seems impossible to discriminate every star of star clusters, but each star is assumed to be distinguishable in our work as there is no reliable instruction about how stars in a cluster can be distinguished. This effect is obvious in the low luminosity part of the main sequences of CMDs. Third, it seems that there are some uncertainties in the observational CMDs. In addition, the effect of superposition in CMDs has not been taken into account in this work, this also affect morphology considerably, especially in crowded regions such as the cluster center.

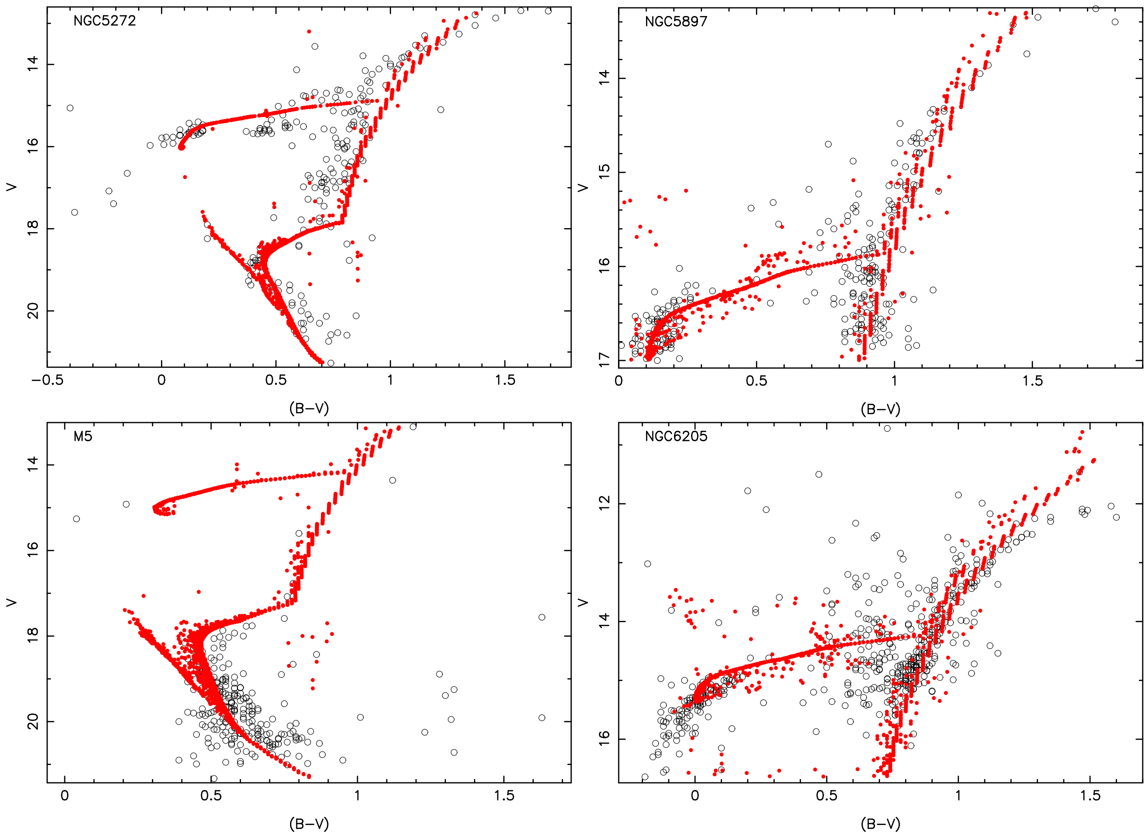

Fig. 2 Similar to Fig.1, but for NGC5272, NGC5897, M5, and NGC6205.

Table 1 Best fit properties (stellar age, metallicity, distance modulus, and reddening) of 12 globular clusters. The results are obtained by comparing the observed CMDs to the CMDs of binary-star stellar populations, and finding the best fit results. Note that a magnitude-weighted method is used in the fitting.

Cluster Name	Age [Gyr]	Metallicity (Z)	(m - M)$_V$ [mag]	$E(B-V)$ [mag]
NGC104	11.3	0.0040	13.4	0.10
NGC2419	9.7	0.0001	20.8	0.00
NGC4147	10.6	0.0001	16.8	0.06
NGC4372	14.3	0.0010	15.4	0.30
NGC5272	12.5	0.0001	15.4	0.16
NGC5897	11.9	0.0001	16.4	0.16
M5	9.5	0.0003	14.8	0.12
NGC6205	12.4	0.0003	14.8	0.04
M10	11.6	0.0010	15.2	0.20
NGC6352	8.4	0.0100	15.6	0.24
NGC6397	11.4	0.0001	13.2	0.10
NGC6809	13.4	0.0003	14.2	0.12

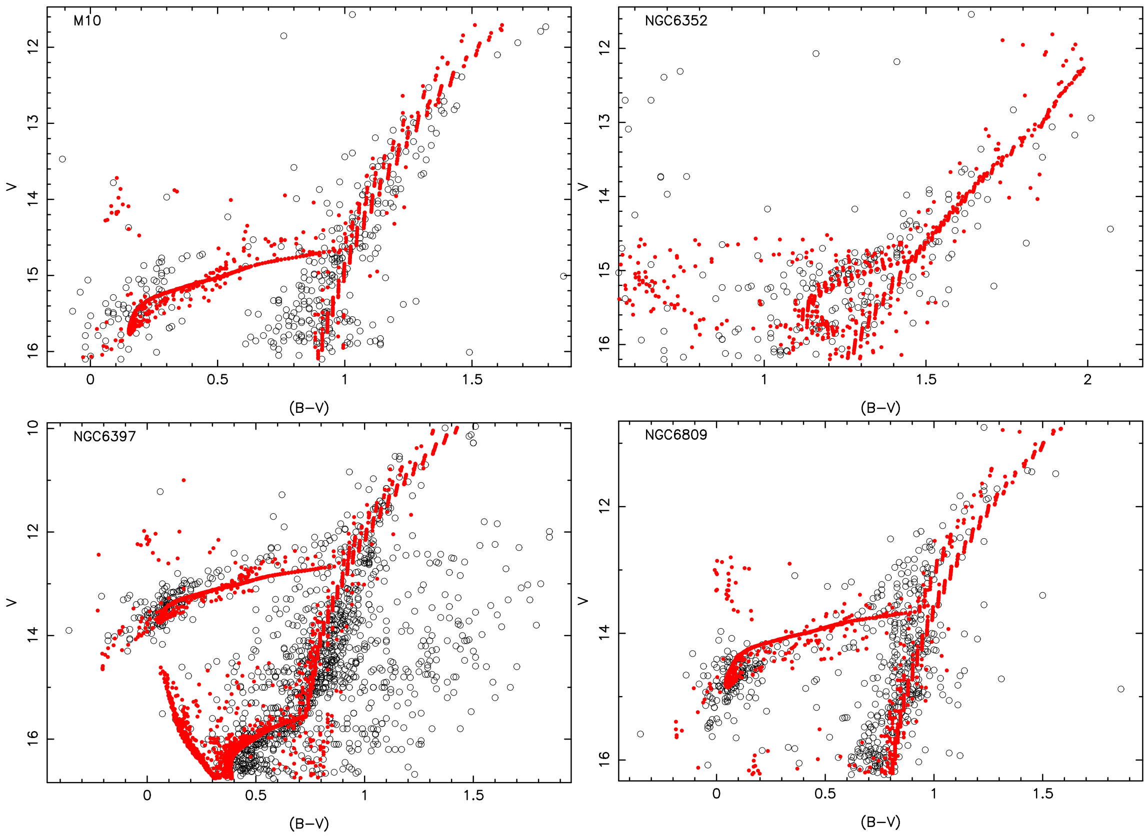

Fig. 3 Similar to Fig.1, but for M10, NGC6352, NGC6397, and NGC6809.

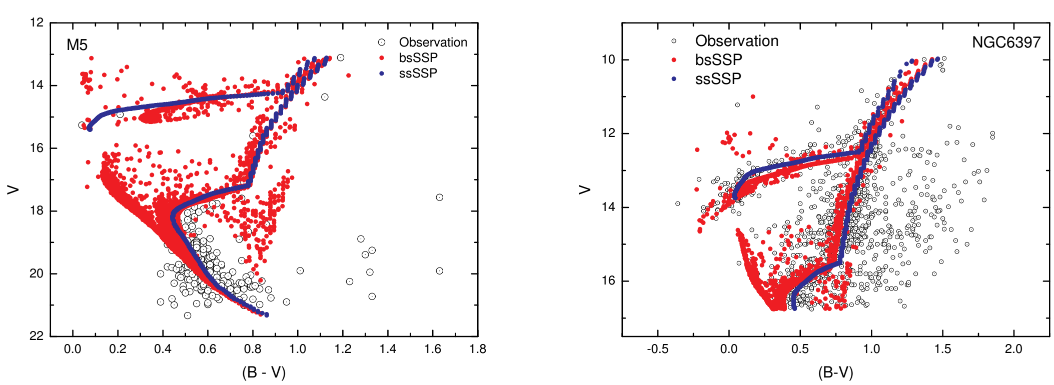

Fig. 4 Comparison of the observational CMDs (black) of star clusters M5 and NGC6397 to the best fit bsSSP (red) and ssSSP (blue) theoretical CMDs. A bsSSP take 50% binaries for its population stars and an ssSSP assumes that all population stars are single stars.

7 CONCLUSIONS

This paper presents a binary-star study for the colour-magnitude diagrams of 12 globular clusters, in which each star is assumed to be distinguishable. It shows that the CMDs of star clusters can be explained well via binary-star populations, although some differences are shown in the comparisons of observational and theoretical CMDs. As a result of the study, some basic properties, i.e., stellar age, metallicity, distance modulus, and colour excess, are determined for the 12 sample clusters. The sample clusters are shown to be old (Age $\geq$ 8.4 Gyr) and metal poor ($Z \leq 0.01$). When we compare the differences between the cluster properties determined respectively by binary- and single-star stellar populations, it shows that the two kinds of population models can give different results for star clusters. Because binary stars are common, the study suggests to use binary method to study the CMDs of star clusters. It also suggests to model the stellar populations of star clusters via binary stars.

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